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Contrasting trends in North Atlantic deep-water formation in the Labrador Sea and Nordic Seas during the Holocene

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[1] The Holocene North Atlantic deep-water formation is studied in a 9,000-year long simulation with a coupled climate model of intermediate complexity, forced by changes in orbital forcing and atmospheric trace gas concentrations. During the experiment, deep-water formation in the Nordic Seas is reduced due to an enhanced influx of sea ice from the Central Arctic, decreasing both surface salinity and density, whereas deep-water formation in the Labrador Sea increases due to surface cooling. This leads to changes in the distribution of oceanic heat transported northwards by the Atlantic Ocean, with less heat released (-120 Wm^{-2} in February) in the Nordic Seas, amplifying the surface cooling and increasing the sea-ice cover. In the Labrador Sea, the oceanic heat release increases slightly (+14 Wm^{-2}), thus dampening locally the cooling trend. The overall Atlantic overturning strength remains constant throughout the experiment. Over the Nordic Seas, reduced evaporation contributes to the surface freshening. **Citation:** Renssen, H., H. Goosse, and T. Fichefet (2005), Contrasting trends in North Atlantic deep-water formation in the Labrador Sea and Nordic Seas during the Holocene, *Geophys. Res. Lett.*, *32*, L08711, doi:10.1029/2005GL022462.

1. Introduction

[2] In the present-day North Atlantic Ocean the two main sites of deep-water formation are the Nordic Seas and the Labrador Sea [*Weaver et al.*, 1999]. In the Nordic Seas, Northeast Atlantic Deep Water (NEADW) is formed, which flows across the Greenland-Scotland ridge to fill the deep levels of the Atlantic, while in the Labrador Sea formation of intermediate water takes place that is known as Labrador Sea Water (LSW). The rate of deep-water formation is an important constituent of the total overturning circulation and the associated northward heat transport in the Atlantic Ocean. There is a growing concern that the North Atlantic Deep-Water formation might be reduced in a warmer climate [e.g., *Wood et al.*, 1999; *Hansen et al.*, 2004]. It is therefore important to understand the natural long-term variations in deep-water formation.

[3] Proxy studies suggest that deep-water formation in the Nordic Seas decreased after 7k (thousand year before present [e.g., *Rasmussen et al.*, 2002]). The opposite trend has been found in the Labrador Sea, where data indicate that a modern-like circulation started slightly before 7k and strengthened afterwards [*Hillaire-Marcel et al.*, 2001; *Solignac et al.*, 2004]. Recent model studies have not been able to capture these contrasting trends [*Cottet-Puinel et al.*, 2004], leaving the underlying mechanism poorly understood. Therefore, we study here the Holocene evolution of deep-water formation in a 9,000-year long transient simulation performed with a coupled global climate model of intermediate complexity.

2. Experimental Design

[4] We applied version 3 of ECBilt-CLIO-VECODE, which describes the coupled atmosphere-sea ice-ocean-vegetation system in three dimensions. The atmospheric component is ECBilt, a quasi-geostrophic model with 3 vertical layers and T21 horizontal resolution [*Opsteegh et al.*, 1998]. The oceanic component CLIO consists of a free-surface, primitive-equation oceanic general circulation model coupled to a dynamic-thermodynamic sea-ice model [*Goosse and Fichefet*, 1999]. CLIO includes 20 levels in the vertical and has a $3° \times 3°$ latitude-longitude horizontal resolution. VECODE is a model that simulates the dynamics of two main terrestrial plant functional types, trees and grasses, and desert as a dummy type [*Brovkin et al.*, 2002]. Details about the model are available at http://www.knmi.nl/onderzk/CKO/ecbilt.html.

[5] To simulate the long-term Holocene climate evolution, we performed a 9,000-year long experiment forced by changes in orbital parameters [*Berger*, 1978] and concentrations in atmospheric CO_2 and CH_4 [*Raynaud et al.*, 2000]. All other forcings (i.e., solar constant, land-sea-ice mask) were kept constant at preindustrial values. The initial conditions for the experiment were derived from a simulation that was run until equilibrium with 9k insolation and trace gas concentrations.

[6] In an earlier paper, we showed that the temperature and precipitation changes north of 60°N were in general agreement with proxy evidence [*Renssen et al.*, 2005]. The simulated response to orbital and greenhouse gas forcing experienced an early optimum (9–8 k) in most of the Arctic, followed by a 1 to 3°C decrease in mean annual temperatures, a reduction in summer precipitation and an expansion of sea-ice cover. Here we focus on the changes in the Labrador Sea and Nordic Seas in winter, as this is the

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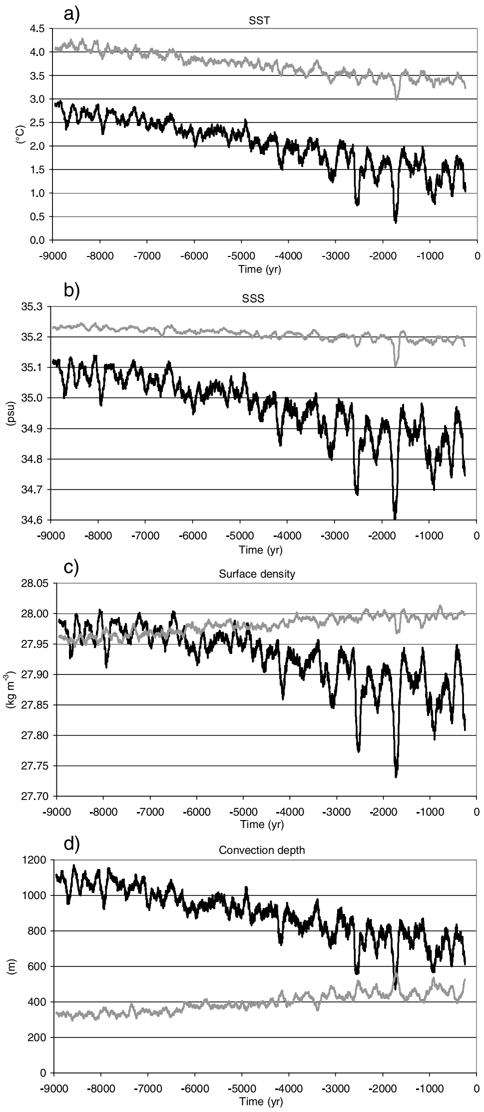

Figure 1. Simulated evolution of key parameters in the Nordic Seas (black line) and Labrador Sea (grey line) during February (i.e., month with maximum convection in the Labrador Sea). Results are averaged over 6 grid cells centered on the main convection sites. The lines depict the 100-point running means. (a) SST, (b) SSS, (c) surface density (note that 1000 kg m^{-3} has been subtracted for convenience) and (d) convection depth (note that maximum convection depths are 2060 m and 1215 m for Nordic and Labrador Seas, respectively).

season during which deep water is primarily formed under influence of the strong surface cooling.

3. Results and Discussion

[7] In the Labrador Sea and Nordic Seas, the winter sea surface salinity (SSS) and temperature (SST) are decreasing during the course of the experiment, leading to fresher and cooler surface waters (Figures 1a–1d and Table 1). These trends have opposite effects on the surface water density, as cooling leads to an increase in density, while freshening results in a decreased density. In the Nordic Seas the changes are relatively large. Compared to the Labrador Sea, the cooling in the Nordic Sea is twice as large (−1.4°C vs. −0.7°C), while the decrease in SSS is five times stronger (−0.26 psu vs. −0.05 psu). These simulated trends are consistent with proxy-based reconstructions from the Labrador Sea [*Solignac et al.*, 2004] and the Nordic Seas [*Koç et al.*, 1993]. In the Labrador Sea, the very small 9k to 0k surface freshening of 0.05 psu is overwhelmed by the surface cooling, resulting in denser surface waters (Figure 1c) and deeper convection (+145 m from 9k to 0k; Figures 1d and 2a). In the Nordic Seas, on the other hand, the long-term freshening is more substantial (−0.26 psu), leading to a reduced surface density (Figure 1c) and convection depth (−381 m from 9k to 0k; Figures 1d and 2a), despite the 1.4°C ocean surface cooling. We found similar contrasting trends in deep-water formation between the Labrador Sea and Nordic Seas in sensitivity experiments with a slightly different setup than our main simulation [see, e.g., *Renssen et al.*, 2005], suggesting that this is a robust result in our model under Holocene forcings.

[8] The long-term winter cooling trends in both convection regions can be linked to changes in insolation. As explained by *Renssen et al.* [2005], the temperature over the Arctic lags the orbital forcing by several months due to the thermal inertia of the system, so that the early Holocene winters were warmer than today throughout the Arctic, despite the reduced insolation during winter. In addition to orbital forcing, the temperatures over the convection regions are influenced by processes that operate on a more local scale.

[9] In the Nordic Seas, the noted decrease in deep-water formation is accompanied by a 9k-to-0k reduction in *local* overturning of 0.4 Sv (1 Sv = 10^6 m^3s^{-1}) or 12% on an annual basis [*Renssen et al.*, 2005]. This reduction does not influence the overall overturning rate of the Atlantic Ocean, as the weaker flow in the Nordic Seas is compensated by the enhanced contribution of LSW. As a result, there is even a slight (statistically insignificant) increase in the total Atlantic deep-water export at 20°S (from 13.5 Sv at 9k to 13.8 Sv at 0k) and in total deep-water production (from 26.3 Sv at 9k to 27.4 Sv at 0k). The total northward heat transport in the Atlantic Ocean remains at a constant level (0.32×10^{15} W at 30°S) from 9k to 0k. These model results agree with available proxy records covering the Holocene, which suggest a weakening of the NEADW production [e.g., *Solignac et al.*, 2004], while showing no trend in the long-term overall Atlantic overturning circulation [e.g., *Oppo et al.*, 2003]. The changes in deep-water formation and local overturning circulation have an impact on the *distribution* of the heat transported northward by the

Table 1. Simulated 9k to 0k Changes in February, Averaged Over the Two Convection Regions

	Labrador Sea	Nordic Seas
SST (°C)	−0.7	−1.4
SAT (°C)	−0.7	−10.5
SSS (psu)	−0.05	−0.26
Surface density (kg m^{-3})	+0.04	−0.11
Convection depth (m)	−145	+381
Ocean-to-atmosphere heat flux (Wm^{-2})	+14	−120
Sea-ice cover (%)	0	+27
Precipitation (mm)	−3	−16
Evaporation (mm)	0	−41

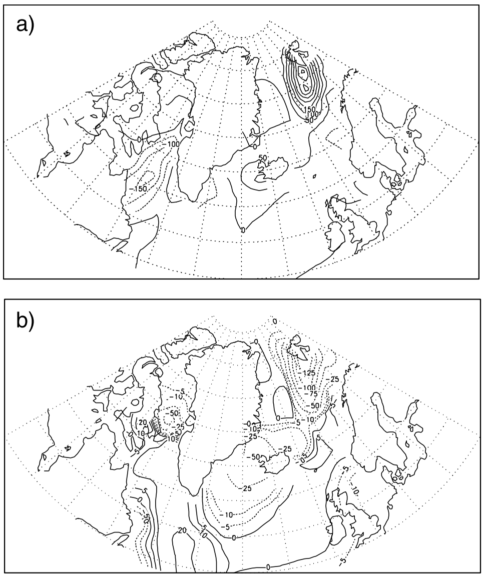

Figure 2. Simulated February 9k minus 0k anomalies in (a) convection depth (in m) and (b) ocean-to-atmosphere heat flux (in Wm^{-2}, upwards is negative).

Atlantic Ocean (Figure 2b). Over the Nordic Seas convection region, the February ocean-to-atmosphere heat release decreases from 9k to 0k by 120 Wm^{-2}, whereas it increases by 10 to 20 Wm^{-2} over the Labrador Sea.

[10] The relatively strong freshening in the Nordic Seas is primarily associated with an increase in sea-ice cover. At the main convection site (South of Svalbard; Figure 2a), the February sea-ice concentration enhances from 16% at 9k to 45% at 0k (Table 1). As practically no local sea-ice formation takes place here, this can be attributed to the increase in southward sea-ice mass transport to the convection site (from 0.043 Sv at 9k to 0.071 Sv at 0k) that is mainly due to the thickening of ice in the Central Arctic during the Holocene [*Renssen et al.*, 2005]. The increased ice transport is accompanied by an enhanced melting of ice at 0k compared to 9k (i.e., twice as large) and thus by an increased ice-related freshwater flux. In contrast, in the Labrador Sea the sea-ice edge stays at the same position (~200 km North of the convection site) and no significant change in sea-ice mass transport is found. As a consequence, the input of freshwater from melting sea-ice remains stable throughout the experiment, resulting in a much lower changes in salinity than in the Nordic Seas. Our results contrast with *Cottet-Puinel et al.* [2004], who found no trends in NEADW formation in Holocene simulations, possibly because the deep-water formation is located more southward than in our case, leading to a reduced impact of the sea-ice export out of the Central Arctic.

[11] The maximum local cooling in the Nordic Seas (−1.4°C at 75°N in February) can be related to the discussed 120 Wm^{-2} 9k-to-0k reduction in ocean-to-atmosphere heat flux (Figure 2b) and to the 27% increase in sea-ice cover (Table 1), which leads to amplified atmospheric cooling through two positive feedbacks (i.e., ice-albedo and ice-insulation). Indeed, the atmosphere over the Nordic Sea cools by more than 10°C during the course of the experiment (Table 1). By contrast, in the Labrador Sea, as the ice edge remains at the same position during the Holocene, no ice-related feedback could take place. The SST reduction is thus smaller and the maximum local surface ocean cooling is located near the Labrador coast (i.e., south of the convection site). This cannot be linked to changes in the ocean-to-atmosphere heat flux (which increases by 10 to 20 Wm^{-2} in February). Instead, it is related to a 9k-to-0k strengthening of the Westerlies (+1 ms^{-1} at 55°N in February), bringing more cold continental air to the area. In turn, this strengthened atmospheric circulation is connected to the enhancement of the meridional temperature gradient, as the Arctic cools substantially during the course of the experiment, while mid and low latitudes experience a slight warming [*Renssen et al.*, 2005]. The Nordic Seas convection area is much less affected by this change in atmospheric circulation due to its more northward position (at ~75°N) compared to the core of the Westerlies at 42°N.

[12] Changes in precipitation and evaporation also have affected local SSS, particularly over the Nordic Seas. Over the two convection regions, evaporation exceeds precipitation in winter, resulting in a negative freshwater input from the atmosphere in this season. From 9k to 0k, a downward trend in both February precipitation and evaporation is simulated over the two convection areas (Table 1). The maximum 9k to 0k precipitation and evaporation anomalies are clearly associated with locations where the ocean surface experiences maximum cooling. Over the Nordic Seas, the reduction in February evaporation is much stronger (110 mm at 9k to 69 mm at 0k) than the decrease in precipitation (79 mm at 9k to 63 mm at 0k), producing a 9k to 0k increase in P-E of 25 mm, thus contributing to the long-term freshening. Over the Labrador Sea the variations are much smaller, with the February precipitation reduction being more substantial (48 mm at 9k to 45 mm at 0k) than the decrease in evaporation (less than 1 mm from 9k to 0k). Hence, over the Labrador Sea, P-E becomes slightly more negative (by 3 mm) in winter, but this effect is very small. The annual averages for the Nordic Seas show the same trends as for winter, but in the Labrador Sea P-E increases on an annual basis from 9k to 0k (by 8 mm), thus explaining the small SSS decrease (Figure 1b).

[13] In the Nordic Seas the 120 Wm^{-2} decrease in oceanic heat release is enhancing the surface cooling already taking place due to orbital forcing. This enforces the increase in sea-ice influx and associated freshwater input, and leads to a local reduction in evaporation, both resulting in a decrease in SSS. This freshening reduces the surface density and overwhelms the opposite effect of the cooling, thus producing a reduction in deep convection (i.e., a positive feedback). In the Labrador Sea, however, the 14 Wm^{-2} increase in heat release tends to damp both the cooling and the increase in deep convection, resulting in a negative feedback that partly counteracts the effect of orbital forcing. The strong interaction between sea ice and convection in the Nordic Seas, and the positive feedbacks on the SST, explain the progressive increase in variability that is absent in the Labrador Sea. Multi-decadal sea-ice anomalies in the Nordic Seas are part of the internal variability in our model and occur more frequent when the climate becomes cooler. They are triggered by specific atmospheric conditions that promote sea-ice transport to the

Svalbard region [see *Goosse et al.*, 2003; *Goosse and Renssen*, 2004].

[14] It should be noted that we have not included the effect of melting ice sheets in our experiment. Reconstructions indicate that the last remnants of the Laurentide Icesheet melted around 7k [*Peltier*, 1994]. The associated meltwater flux is estimated at 0.08 Sv between 9 and 8k, of which only a portion drained directly into the Labrador Sea [*Licciardi et al.*, 1999]. After 8k the meltwater flux from the Laurentide ice sheet became very small (less than 0.01 Sv). Consequently, in the first thousand years of our experiment, the SSS in the Labrador Sea is probably overestimated, implying that the simulated upward trend in deep-water formation was been more pronounced than in our simulation. This would be consistent with reconstructions that suggest that in the Labrador Sea a modern-like circulation started around 7k [*Hillaire-Marcel et al.*, 2001; *Solignac et al.*, 2004] and with the model simulations of *Cottet-Puinel et al.* [2004] that overestimated LSW formation when Laurentide meltwater was not accounted for.

4. Concluding Remarks

[15] Our simulations suggest that in the warmer early Holocene climate, deep-water formation was stronger in the Nordic Seas than today, primarily because of a reduced sea-ice cover in the early Holocene and a relatively strong evaporation. In contrast, the opposite trend is found for the Labrador Sea, since here the simulated deep-water formation is governed by the surface cooling, which is less pronounced in the early Holocene than in the modern climate. These simulation results are in good agreement with available proxy evidence, suggesting that our findings provide a reasonable explanation for the observed Holocene trends in North Atlantic deep-water formation.

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